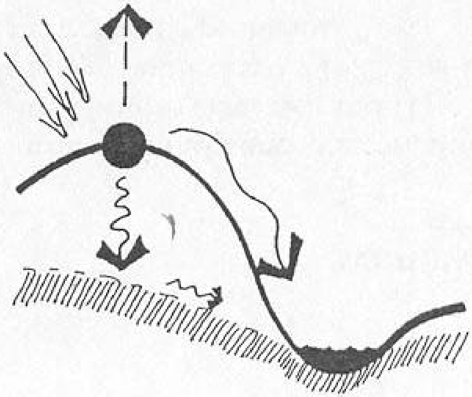
What Happens to Water:
A Handbook on Hydrology

by Jan Mueller

Edited by Jonathan M. Labaree and Meg Ogden



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Chapter One

Introduction

A lot can happen to water between the time it falls as rain or snow and the point where it unites with a stream, lake, or ground water reservoir. Exactly what does or does not happen influences the quality, quantity, and ecological health of our water.

As water travels through the landscape, it encounters countless surfaces—plants, buildings, soil, rocks, and pavement—each of which has a different impact on it. Along its varied pathways, water interacts with land through a variety of processes. These processes determine where water goes: whether it quickly evaporates back to the atmosphere, lingers on the land surface, soaks into the ground, or flows over land.

After Chapter One's introduction of basic concepts, such as the water cycle, water budgets, and watersheds, Chapter Two explains the major land-water processes. Using a hypothetical watershed, Chapter Three explains how to synthesize individual land-water processes in order to map hydrologic zones, which provide insight to what happens to water as it travels through a watershed. Chapter Four discusses the implications that hydrologic zones have for designing land use practices that minimize impacts on water resources.

Intended for developers, conservationists, public officials, and citizens, this handbook is a simplified introduction to hydrology. It is not meant to provide all of the answers. Rather, it outlines basic concepts of hydrology and poses critical questions that need to be asked to understand how land and its uses affect water resources.

The terms *land form* and *land cover* appear throughout this handbook. Land form includes land's shape, slope, soil, and texture. Land cover refers to what is on the surface: houses, fields, forests, or wetlands. Land form and cover combine to influence what happens to water. The broader term *land* includes both form and cover.

The Water Cycle & Water Budgets

The water cycle (Figure 1) represents the path of water as it moves from the atmosphere, through the landscape to lakes and oceans, and back to the atmosphere. We notice part of the water cycle when water falls as rain or snow. We tend to forget about water after it hits the ground, noticing it again only when it re-emerges in a stream or pond. It is during this phase of its cycle when water is least noticeable that humans most influence the quality, movement, and distribution of water. For this reason, this handbook focuses primarily on the processes that characterize how land form and land use affect the water cycle. These processes include:

- **Interception** - water caught by and evaporated from vegetation
- **Depression Storage** - water standing on land surface
- **Infiltration** - water moving into soil
- **Soil Water Storage** - water held within soil
- **Transpiration** - water moved by plants to atmosphere
- **Ground Water Recharge** - water seeping to ground water
- **Runoff** - water moving over land surface
- **Erosion** - water dislodging and transporting soil

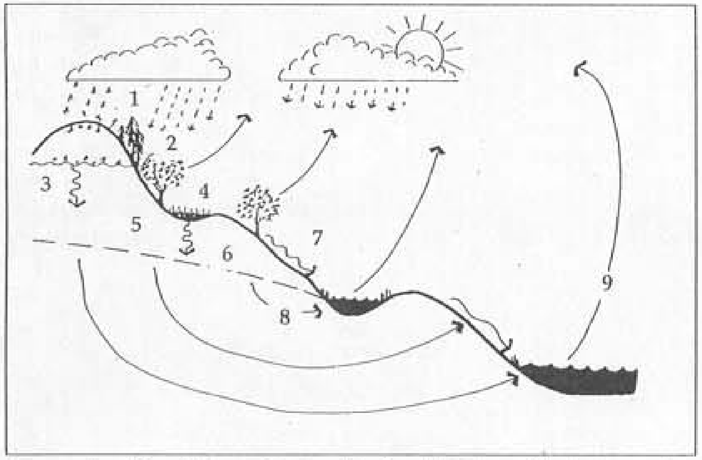

Figure 1. The Water Cycle. 1) Precipitation, 2) Interception, 3) Infiltration, 4) Depression Storage, 5) Soil Water Storage, 6) Ground Wa[illegible]charge, 7) Runoff, 8) Sub-surface Flow, 9) Evaporation.

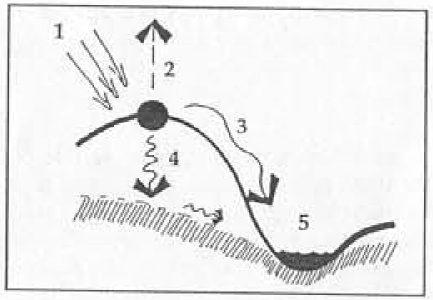

Figure 2. The Water Budget.
1. Precipitation
2. Evapotranspiration
3. Storm Runoff
4. Ground Water Recharge
5. Storage

Related to the water cycle, a **water budget** (Figure 2) describes how water that enters a watershed through precipitation leaves that watershed in one of the following four ways:

- **Evapotranspiration** - water returned to atmosphere
- **Surface Runoff** - water moved over land to streams and rivers
- **Ground Water Recharge** - water drained into ground
- **Storage** - water stored on or near land surface

Over time, the amount of water entering a system (precipitation) must equal the amount leaving it. Thus:

Precipitation = Surface Runoff + Ground Water Recharge + Evapotranspiration + Storage

Hydrologists usually only include evapotranspiration, ground water recharge, and surface runoff in estimating water budgets since water in storage eventually evaporates, runs over the surface, or joins ground water. Scientists use a water budget to define a sub-watershed's hydrologic zones. These zones characterize how land form and land use combine to determine what happens to water.

Land's Influence Over Water

Land exerts its influence over water in one of three general ways: flow regulation, storage, and filtration.

Flow Regulation

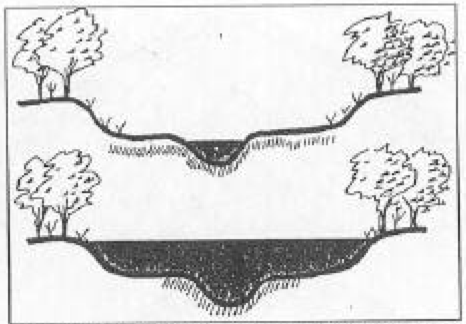

Figure 3. Flow levels. Average Base Flow (top) and Storm Flow (bottom).

Water flow in streams and rivers varies with local weather patterns. Under any given weather pattern, land factors—land cover, soil, topography, and geology—regulate both storm flow and base flow (Figure 3). Storm flow is the rise in stream flow volume resulting from rain or snowmelt runoff. Base flow is the volume of stream flow between runoff events, typically fed by ground water or water held in lakes and wetlands. Natural land forms tend to absorb water, both in the soil and in vegetation, and releases it slowly into streams.

Storage

Land stores water on plant surfaces, as well as in puddles and ponds, soil, and underground rock formations (Figure 4). In dry weather, this stored water releases slowly to rivers, streams, ground water, and the atmosphere. The storage period may be short: water on a leaf, for example, may evaporate in a matter of minutes. It can also be very long: some ground water remains in deep layers of rock for millions of years. Overall, land can store huge amounts of water—more than 95 percent of the world's unfrozen fresh water is stored as ground water.

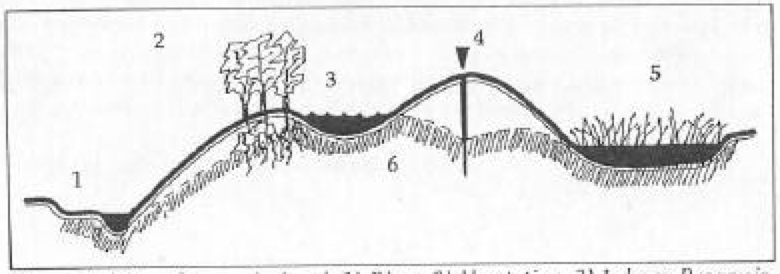

Figure 4. Water Storage in Land. 1) River, 2) Vegetation, 3) Lake or Reservoir, 4) Well, 5) Wetland. 6) Ground Water.

The roads, parking lots, lawns, and buildings of developed areas divert water directly into rivers and streams and away from surface or underground storage. This has significant ecological impacts as water availability, both on the surface and in the soil, affects the survival and distribution of many species. Since ground water, wetlands, and lakes provide most water to streams during dry weather, reducing water in storage also reduces flow in streams.

Water Treatment

Bacteria, plants, and soil (especially clay and organic particles) break down or immobilize many pollutants and nutrients (Figure 5). The longer water remains in the soil or on the surface of the ground, the cleaner it becomes. As a result, certain areas in the landscape play a particularly critical water treatment role: wetlands and vegetative buffers capture and filter surface runoff, while floodplains remove sediments, nutrients, and pollutants from flood waters. Land form and land cover affect water quality—temperature, pH, color, and concentrations of dissolved and suspended solids.

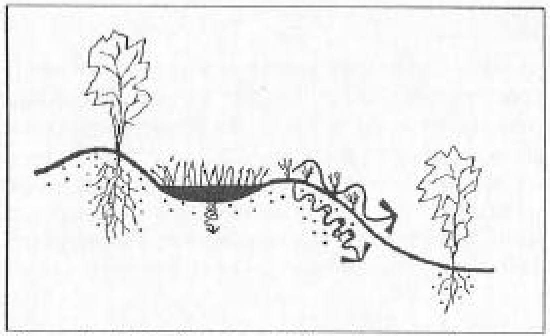

Figure 5. Water Treatment. Ground cover plants and plant debris slow runoff which allows sediment to settle and water to seep into the ground where bacteria, soil particles, and plants filter many pollutants.

Watersheds & Subwatersheds

The basic unit for understanding how land interacts with water is the watershed. A watershed refers to a basin of land which catches rain or snow and directs it down slope to a point in a river or stream—an outlet point. Hydrologists also define watersheds by choosing a point in the landscape and determining the land area that captures water and drains it through that point.

A watershed can be as large as an entire river valley or as small as the area draining into a small tributary stream. The unique topography of any landscape creates a system of interconnected basins, smaller watersheds—or sub-watersheds—nestled within larger ones (see Figure 6).

While surface drainage defines watersheds and subwatersheds, ground water may not move through the landscape in the same way as surface water. Ground water can flow across watershed boundaries since it follows geologic structures. At the scale of whole watersheds, however, ground water movement generally matches surface watersheds.

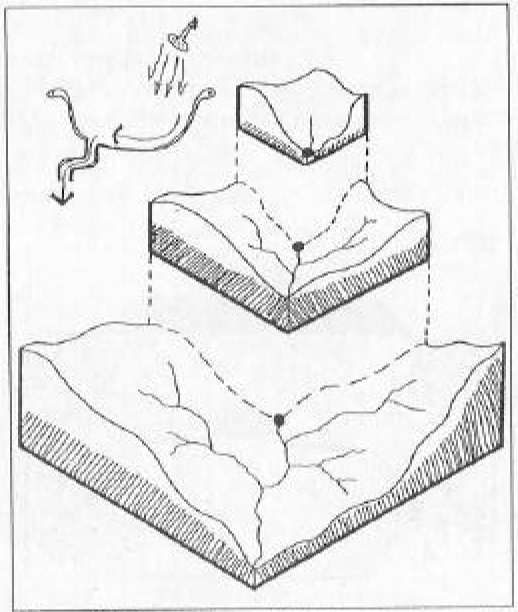

Figure 6. Watersheds are like tubs capturing water and directing it towards an outlet point.

Chapter Two

Land-Water Processes

Land-water processes are interactions between land form, land cover, and water. Both climate and land factors influence these processes. While human influence over the climactic is of great concern, this handbook deals largely with land factors. Land factors such as soil, slope, geology, and land cover combine to influence what happens to water as it moves through a watershed. Small variations in these factors can affect water. Understanding the following land-water processes will aid efforts to develop land use practices that minimize detrimental impacts on water resources:

- Interception
- Infiltration
- Depression Storage
- Soil Water Storage
- Transpiration
- Ground Water Recharge
- Storm Runoff
- Erosion

Interception

Leaves, stems, and fallen litter of trees and plants catch and hold significant amounts of rain and snow. Most of this water evaporates back to the atmosphere—a process known as interception (see Figure 7). Studies have shown that interception of rain is often higher than that of snow, which typically melts and drips to the ground. Plain surfaces, such as roofs, walls, and roads, also account for minor amounts of interception.

Different types of land cover intercept different percentages of rainfall depending on the total density and seasonal variation of vegetation surfaces—trees, shrubs, ground cover plants, and plant litter. Interception ranges from nearly zero for bare soil to more than 40 percent of annual rainfall in some evergreen forests. Conifers intercept more precipitation

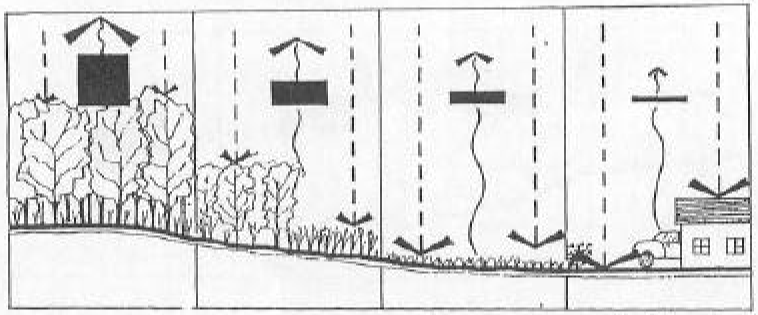

Figure 7. Interception. The greatest interception occurs on the left where large trees dominate the landscape. Highly developed land, such as on the right, intercepts very little precipitation.

than deciduous trees on an annual basis because needles are more dense than leaves and they are present all year. Thick, full-grown stands of grass intercept almost as much water as trees. Dense crops, such as alfalfa, contribute to interception much like grasses, while row crops, such as corn, present more bare ground and generally lower vegetation density. Forest litter—leaves, twigs, etc.—intercepts approximately two to four percent of rainfall.

Climactic conditions—rain intensity, temperature, wind velocity, and humidity—also influence interception. For example, light rains in warm weather result in higher interception than a cloudburst downpour during the cold season.

Hydrologists debate the importance of interception in water budgets. Some studies suggest that interception mostly displaces water that plants would otherwise transpire (see page 15). The issue is often ignored by treating the combined result, evapotranspiration, as a single phenomenon.

Infiltration

Water not intercepted by leaves or other surfaces eventually reaches the soil. Some or all of this water moves into the soil by the force of gravity—a process called infiltration (see Figure 8). The rate at which a given type of soil can absorb water is its infiltration capacity. Infiltration capacity depends on the size of pores between soil particles, and on how well they are connected. Pore space is, in turn, a function of soil texture (the mix of different particle sizes, i.e. clay, silt, or sand) and soil structure (how well the soil is aggregated into clumps).

Infiltration varies according to soil structure and land cover. It is fastest in coarse-textured soils with similar-sized particles and well-connected pores. In fine-textured soils, where smaller particles leave little pore space, infiltration rates tend to be slow. Some clay soils actually expand and seal when wet, preventing infiltration altogether. Organic matter and secretions from both plant roots and soil organisms help form soil into clumps which increase infiltration capacity by increasing pore size and creating connections among pores. Plant roots also facilitate flow by creating channels in soil.

Infiltration generally declines rapidly during the early part of a storm, reaching a near constant value after one to two hours when fine pores in surface soil become filled, reducing the soil's capacity to accept water. This final low rate of infiltration typically determines how much runoff is generated because when the soil is saturated, water stays on the surface, collecting in puddles and forming rivulets. In addition, water only infiltrates soil where there are unfilled pores to accept it. Hence, soils that resist infiltration, such as clays, or are always saturated, such as in a wetland, tend to generate runoff. Note that in wetlands, runoff may travel to a nearby depression and be stored on the surface. This is why wetlands both generate runoff, but control flooding.

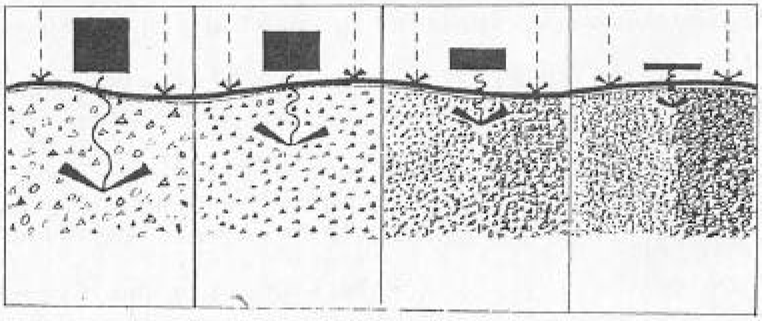

Figure 8. Infiltration. Greatest infiltration occurs in well-aggregated, loosely compacted soil (left). Fine grained, compacted soil results in little infiltration (right).

Depression Storage

If rainfall exceeds the ground's capacity to absorb water, it begins to collect and fill surface depressions, to become depression storage (see Figure 9). These depressions might be as small as a puddle or as large as a pond. Some of this water returns to the atmosphere through evaporation, while the remainder slowly infiltrates the soil. If soil drains poorly, water may remain on the surface for days. Water may also become surface runoff, which begins once rain fills a depression.

Depression storage capacity varies with slope, land form, and surface texture. It is greatest on land surfaces that are level or gently-sloping, naturally rough or graded to enhance depressions, or abundant in larger depressions like ponds. It is conversely lower on steeper areas which have been highly disturbed or graded to drain more quickly. Storage in small depressions may retain for 0.05" of rainfall on steep hills and up to 2.0" on gently sloping agricultural land where furrows or terraces have enhanced surface depressions.

Poorly drained soils are distinguishable by fine texture, a high water table, and impervious layers.

Better drained soils, conversely, have coarse texture, a low water table, and no impervious layer.

Poorly drained (see box) surface depressions, consisting of saturated soil or standing water for part or all of the year, typically form what are known as wetlands. In addition to storing water, these wet depressions offer important habitat for birds, insects, and amphibians. Better drained depressions may hold water too briefly to be considered wetlands, but still act as important retention basins.

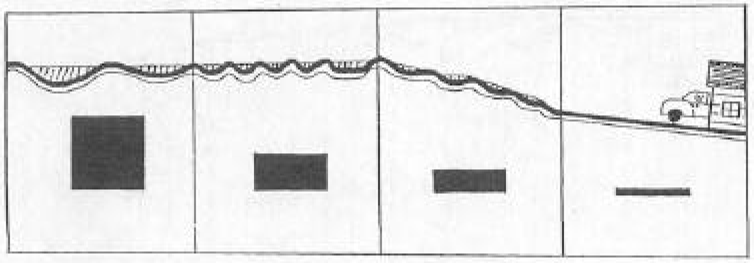

Figure 9. Depression Storage. Land with an undulating surface (left) will store more water on its surface than smooth land such as the paved area on the right.

Distinguishing between good and poor drainage, or more and less wet, is difficult. For the purpose of this handbook, it is more important to understand when and where water is collecting and where it goes from there.

Soil Water Storage

Soil stores water in two ways—in macro-pores and in micro-pores. Water that fills macro-pores (relatively large voids) tends to drain downward to the water table by the force of gravity. Water in small micro-pores between fine particles is held up against the force of gravity by capillary force (see Figure 10).

When rain or snowmelt is heavy enough, water fills all large macro-pores, saturating the soil. Gravity typically drains water out of macro-pores within two or three days. Soil remains saturated much longer, though, where a high water table or a perched water table prevents drainage.

The amount of water stored in saturated soils (in a wetland, for example) is equal to its porosity—the proportion of a soil's volume that is pores. Fine-textured silts and clays have higher porosities and, hence, higher storage and saturation capacities than coarse-textured sandy soils. However, water infiltrates very slowly into fine soils, so coarse sandy soils often become saturated more readily.

The **water table** generally defines the level of ground water. Sometimes, an impervious layer in soil, such as a layer of clay, prevents water from draining down to ground water. This creates a "perched water table" where soil remains saturated but is above the true ground water level.

In better-drained soils, water drains easily from macro-pores, with some remaining in micro-pores. The maximum amount of water that soils store in micropores is known as field capacity. Plants draw water from micropores until a point when soil particles hold water too tightly for them to extract it. Soil, therefore, also has an *available* water capacity, that is often less than field capacity because the water that remains in micro-pores in not available for the use of plants.

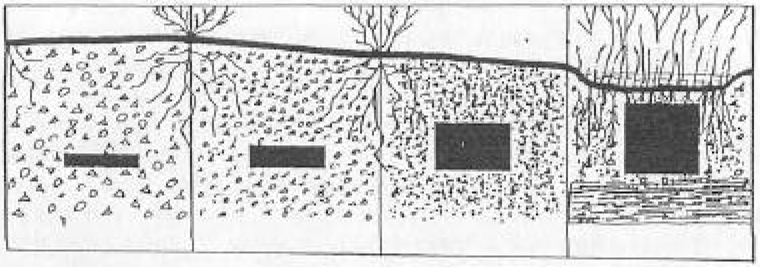

Figure 10. Soil Water Storage. Large grained soils such as sand (left) will hold less water than fine grained soils such as clays (right) since the spaces between the grains are too large to exert capillary force sufficient to overcome gravity.

Soil water storage capacity varies not only with soil texture and organic matter, but also with unfilled storage space and rain frequency. After heavy rains, soil moisture is at or above field capacity because water fills micropores. Over time, as water evaporates or gets taken up by plants, unfilled capacity increases.

When soil water exceeds field capacity, it drains downward to join ground water. Differences in soil storage capacity, therefore, have a pivotal role in regulating ground water recharge. Soils with high infiltration rates and low water storage capacity, such as sands, will recharge ground water more readily than soils with low infiltration rates and high water storage characteristics, such as clays.

Water stored in soil for sufficient time benefits from natural filtering. Many nutrients and pollutants are neutralized or immobilized by soil microbe reactions, plant uptake, or adhesion to clay particles and organic matter. Others are more likely to persist in or leach through the soil; nitrates, for example, a common pollutant from septic systems, is very mobile in soil water and, if not used by plants, tends to leach downward and contaminate ground water.

Transpiration

Plants take up water in the soil through their roots, then transport it to leaf surfaces where it evaporates back to the atmosphere—a process

known as transpiration (see Figure 11). Trees transpire large amounts of water; smaller plants somewhat less. More than two-thirds of the precipitation falling on the U.S. returns to the atmosphere by transpiration and evaporation. Difficult to measure separately, hydrologists consider them together as evapotranspiration.

Conditions limiting evaporation, such as solar radiation and temperature, influence plant transpiration. Where climactic conditions are constant, differences in soil and vegetation are responsible for variations in transpiration.

When soil water is plentiful, there is a maximum rate at which a land area loses water to evapotranspiration—known as its potential evapotranspiration rate. Potential evapotranspiration rates vary among different types of vegetation. For example, one study in England observed that on a sunny day a plot of grass lost 0.1" of water while a corresponding plot of brussel sprouts lost 0.16". Forest trees lose water at even greater rates.

Actual evapotranspiration is usually less than the potential rate. Potential evapotranspiration rates occur only when soil water is abundantly available to plants. When precipitation is less than potential evapotranspiration, plant roots start to draw down soil moisture to meet their evapotranspiration demands. When soil moisture declines, soil particles hold the remaining water more tightly making it difficult for roots to take it up.

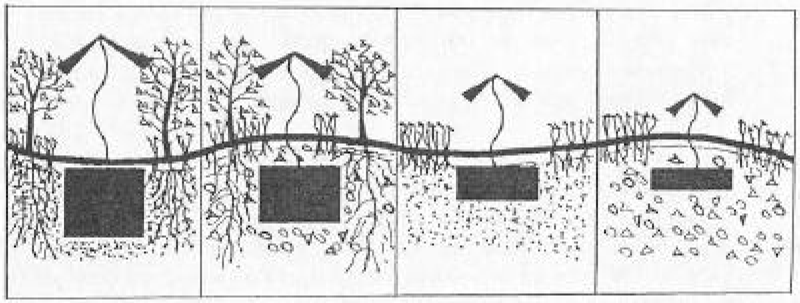

Figure 11. Transpiration. Transpiration is greatest where large trees dominate the landscape (left). Small plants in well-drained soils transpire the least water to the atmosphere.

As with infiltration, soil type influences transpiration, especially during dry weather. Transpiration rates drop off quickly in soils with low storage capacities because little water is available for plants to use. When soil moisture is limited, differences in the depth and density of plant roots become significant. Areas with dense vegetation—a closed canopy of trees, understory shrubs, and ground cover—are likely to have greater root depth and density, and, hence, greater transpiration rates. When soil moisture is not limited, larger and denser trees and plants transpire more water than their sparser counterparts.

Ground Water Recharge

Ground water recharge occurs when soil moisture is at maximum capacity and water infiltrates the soil faster than it leaves by evapotranspiration (see Figure 12). Water continues moving downward through layers of soil and underlying geology until it reaches ground water (the water table), where voids between particles or fissures in bedrock are then filled. Water may also travel down slope under the surface until it reaches a stream. This is called ground water flow.

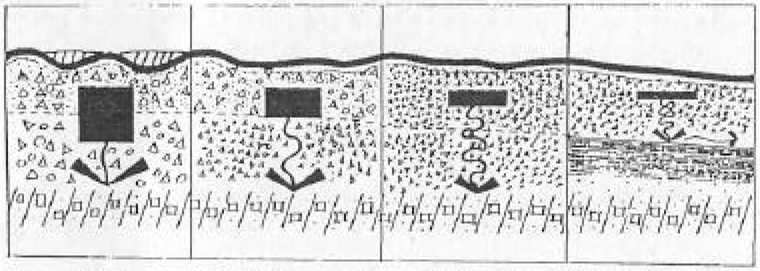

Figure 12. Ground Water Recharge. Areas with low soil water capacity will tend to contribute more to ground water (left). Areas with a non-permeable layer (right) might contribute little to ground water as water is diverted away and into a stream.

When infiltration is less than potential evapotranspiration, soil moisture falls and no ground water recharge occurs. When infiltration exceeds potential evapotranspiration, soil is replenished by a moisture surplus. Furthermore, when infiltration exceeds potential evapotranspiration, and soil moisture is at maximum capacity, water travels downward to become grou[illegible]ater.

Downward drainage of water is limited by the rate at which a given soil or geologic material can conduct water—known as its permeability. The mobility of ground water itself also depends on the permeability of surrounding material. Due to variations in permeability, different watershed areas are more hydrologically isolated from or hydrologically connected to significant ground water reservoirs.

Areas more hydrologically connected to ground water reservoirs have higher recharge potential. Actual recharge depends on how much water escapes runoff and evapotranspiration to reach ground water. While highly connected areas have high per-acre recharge rates, less-connected areas that are large will contribute significantly to total ground water recharge. Land use changes that reduce ground water recharge in highly connected areas can have a disproportionately large impact on total recharge. Interfering with ground water recharge can reduce base stream flow, because ground water typically feeds streams. Highly connected areas are also sensitive to ground water contamination since infiltrating water can move rapidly into the water table with little filtering by soil and plants.

Surface Runoff

When rain or snowmelt fails to infiltrate the ground, and surface depressions become full, water begins to travel down slope as surface runoff or overland flow (see Figure 13). Overland flow can vary from trickles of small volume and slow velocity to accelerating flows of large volume and high velocity. It is generally described as one of three types:

- Sheet Flow - occurs mostly in natural areas as slowest and lowest energy flow—small rivulets flowing from one small surface depression to another.
- Shallow Concentrated Flow - occurs when sheet flow runoff increases in depth to form larger continuous streams of water, but without sufficient velocity and energy to develop significant channels.
- Channelized Flow - occurs when shallow concentrated flow gathers enough velocity, depth, and energy to cut gullies or channels.

Where water runs along the surface slowly, following a sinuous path before reaching a permanent stream, it is more likely to infiltrate the soil, collect in depressions, or evaporate. Topography and ground cover control both the velocity and flow path of surface runoff. Ground cover provides resistance to overland flow—bare soil offers much less resistance than a stand of tall grass. Land form dictates where runoff concentrates and disperses as it moves down slope. Where land forms are convex, water tends to spread out and decrease in depth as it travels down slope. On concave slopes, water tends to concentrate and increase in depth—an effect naturally amplified with steeper slopes.

As water concentrates and travels through the watershed, some overland flow may move below the surface, while some sub-surface flow may reemerge to the surface. Landscape features—vegetative buffers, wetlands, and floodplains—act to dissipate the energy of runoff and can be particularly important in controlling its impacts.

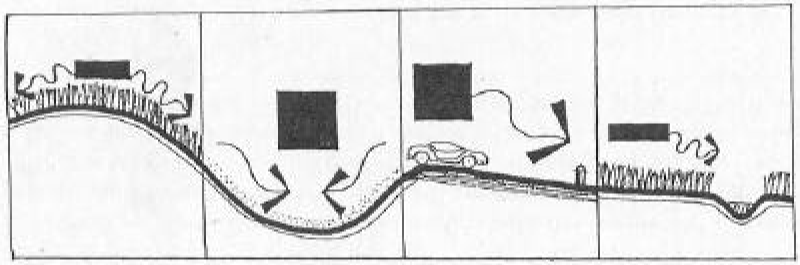

Figure 13. Surface Runoff. Topography and ground cover both affect surface runoff. More vegetation and less slope will result in the least runoff while less vegetation and greater slope result in the most runoff. Convex areas (far left) will have less runoff than concave areas (middle left).

Erosion

Closely related to surface runoff, soil erosion (see Figure 14) occurs where either the impact of raindrops or the force of runoff dislodges and moves particles down slope. Most erosion occurs during or after heavy storms. Plant roots (binding soil particles together), ground plants, and plant litter provide protection from erosion by covering soil particles and reducing runoff velocity.

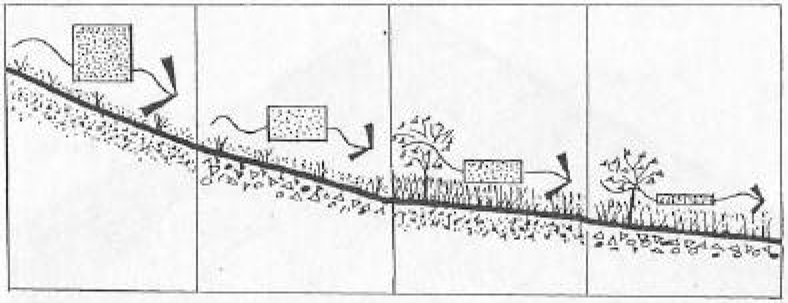

Figure 14. Erosion is greatest in areas with steep slopes and little vegetation (left) and least in shallow slopes with a lot of vegetation (right).

Soil types vary in their tendency to erode. Finer particles, especially silts, are generally carried more easily than larger particles like sand. Some very fine clay particles, however, cohere and resist erosion better than larger particles. In addition, clay content in soil helps bind particles into clumps which inhibit erosion by enhancing infiltration. Very high clay content, however, can reduce infiltration and therefore increase erosion. Organic matter in soil also enhances soil aggregation and helps resist erosion.

Defining Hydrologic Zones

Water moving through a watershed will eventually leave by one of three processes: runoff, ground water recharge, or evapotranspiration. In order to evaluate land use, either current or planned, for its impact on water resources, it is important to know which of these three processes accounts for most of the water moving through the area. Areas that produce a lot of runoff require different design considerations than areas that recharge the ground water or contribute greatly to evapotranspiration. Combining the effects of the land-water processes introduced in Chapter Two lead to delineating a watershed into hydrologic zones—areas where either runoff, ground water recharge, or evapotranspiration dominate the water budget.

Just as you might draw up a budget for your household finances to account for income and expenses, so hydrologists devise a water budget to account for what happens to water in a watershed. Over time, the amount of water entering a watershed through precipitation equals the amount that leaves as runoff, ground water, or vapor. Thus:

Precipitation = **Surface Runoff + Ground Water Recharge + Evapotranspiration**

This is a simplified version of the equation presented in the Introduction (see page 5). Unlike that equation, it does not include water storage. Hydrologists generally do not consider stored water in a budget since water in ponds, puddles, or lakes ultimately becomes runoff in streams and rivers, drains to join ground water, or evaporates into the atmosphere. Water retained in soil either remains there, joins ground water or is taken up by plants to be transpired into the atmosphere.

Throughout this chapter, a hypothetical watershed (Figure 15) will help show how variations in land use, topography, soil type, moisture condition, and other factors combine to create zones where surface runoff, evapotranspiration, or ground water recharge dominate the water budget. The dark black lines (not the roads in the upper right) delineate broad landscape characteristics—mature forest, secondary growth, field, development, and wetland. To map hydrologic zones, hydrologists account for each element of the water budget.

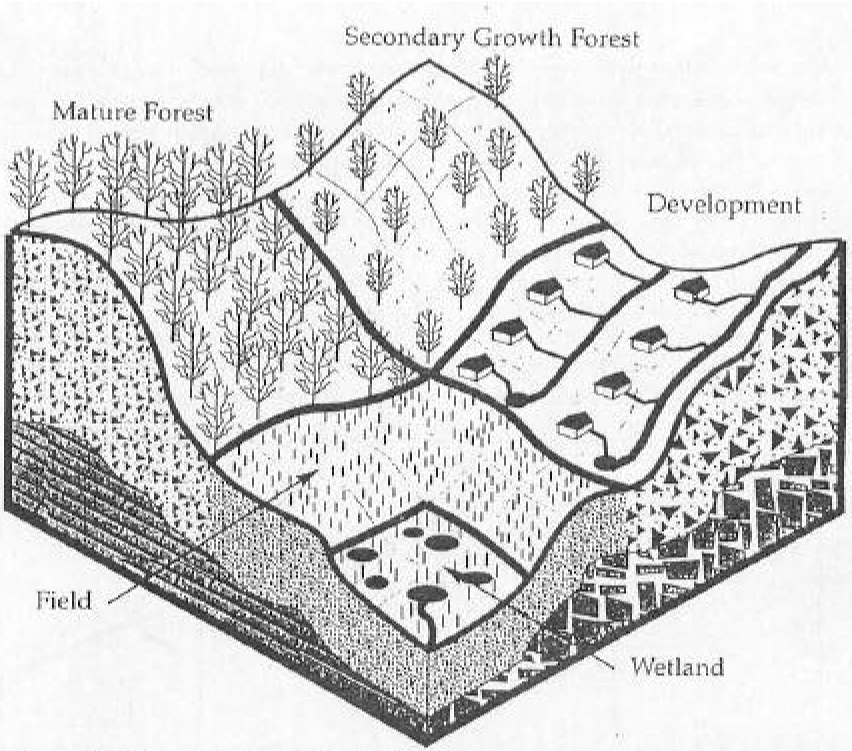

Figure 15. A Hypothetical Watershed. Take a moment to examine this hypothetical watershed in a temperate zone. Note the variations in slope, land cover, soil type, and bedrock. This graphic appears throughout the chapter to describe how the processes discussed in Chapter Two interact with each other to determine how water moves through the landscape. Note: a "secondary-growth forest" could be a field returning to forest or a recently logged forest.

Accounting for Elements of the Water Budget

Precipitation

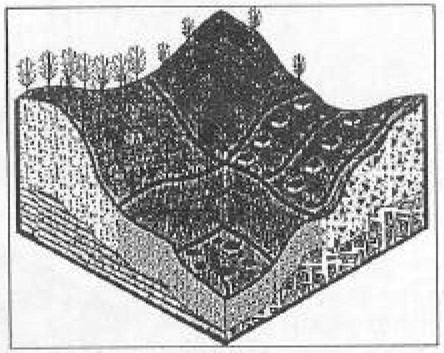

Figure 16. For simplicity, precipitation will be uniform throughout the watershed.

Estimating precipitation relies on data from the U.S. National Weather Service's rain and snow gauging stations. The amount of rain and snow falling over a watershed can be quite variable, however, especially where elevation changes significantly. It is helpful, therefore, to average data from more than one station, in and around a watershed; commonly used methods for averaging precipitation data can be found in most hydrology texts, such as Dunne and Leopold's *Water in Environmental Planning*.

For this discussion, precipitation is assumed to be uniform (Figure 16).

Surface Runoff

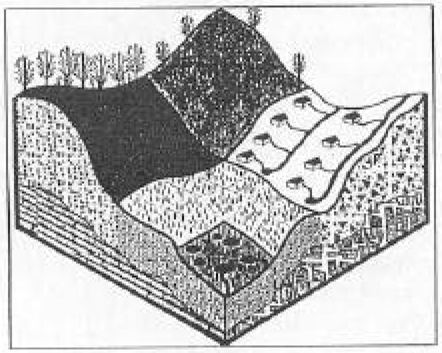

Figure 17. Interception. Darker shades depict greater interception

Surface runoff results when rain or snowmelt exceeds the land's interception, depression storage, and infiltration capacities. Thus, runoff will be greatest where interception, depression storage, and infiltration are lowest.

Interception capacity correlates directly with amount and type of land cover. Figure 17 shows interception rates in the hypothetical watershed. The mature forest intercepts the most water because it has a dense and multi-layered cover of vegetation. The secondary growth forest intercepts slightly less water because its vegetation is not as thick. Although the wetland has low vegetation, it intercepts roughly the same amount of precipitation as the secondary forest because its vegetation is quite dense. The grasses in the field will intercept a bit less than the secondary forest while the developed area traps the least amount of water because buildings, pavement, and lawns dominate that area. High interception levels leave less water for runoff.

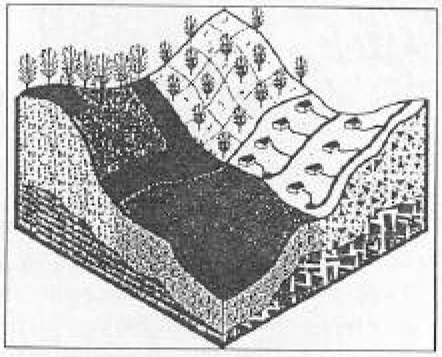

Figure 18. Depression Storage. Darker shades represent greater depression storage.

Both slope and terrain determine depression storage. Areas with steep slopes and smooth terrain will have few cavities and depressions to store water. Flatter areas and those with rough terrain will have many small hollows or ponds for storing water on the surface. Figure 18 shows the depression storage capacity for the hypothetical watershed. Runoff will be lowest where surface depression hold a lot of water.

Infiltration rates vary according to soil type and plant cover. Well-drained soils will accept water more readily than poorly drained soils. Soils with large, well-connected pores, such as sands, will have high infiltration while soils such as clays with small, poorly connected pores will inhibit infiltration. Where soil conditions are the same, infiltration will be less where transpiration is greater because plants will take up water rather than allowing it to infiltrate down. Figure 19 (page 24) depicts infiltration rates in the hypothetical watershed. Note that in the developed area, roads have virtually no infiltration capacity because paved surfaces do not allow water to enter the soil. High infiltration capacity leads to low runoff because water is seeping into the ground.

Mapping the watershed for runoff potential requires combining the effects of interception, depression storage, and infiltration. Areas where these effects are high leave little water for runoff. Where they are low, a

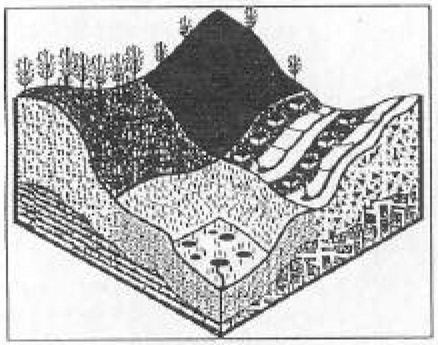

Figure 19. *Infiltration. Darker shades show greater infiltration rates.*

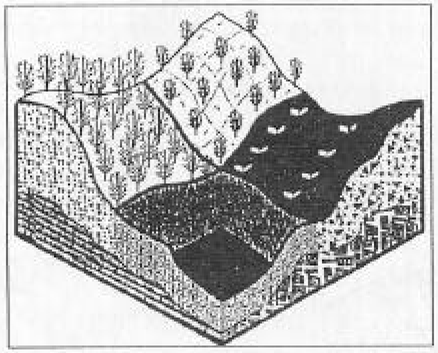

Figure 20. *Runoff Zones. The darker shaded areas denote high runoff.*

lot of water runs off. Figure 20 shows the runoff potential of each of the watershed's dominate zones. Note that both the developed area and the wetland have high runoff. In the developed area, low interception and infiltration rates combine to create runoff. In the wetland, the very low infiltration rate results in high runoff. Runoff is least in the mature forest where so much water gets intercepted and where infiltration rates are relatively high. Moderate interception in the secondary growth forest yields moderate runoffs. The field's low infiltration and interception rates result in rather high runoff. Indeed, if you stand at the edge of a field after a rain storm, you will notice a lot of water draining from it. Likewise, the culverts and drains in developed areas are usually full after even a little rain.

Ground Water Recharge

Ground water recharge occurs only when soil moisture is at maximum capacity and water infiltrates into the soil faster than it leaves by evapotranspiration. Where soil water storage and evapotranspiration are low and infiltration is high, ground water recharge will be high.

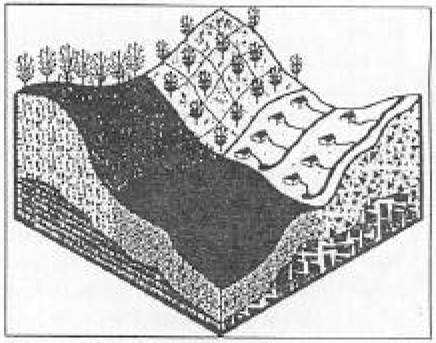

Figure 21. *Soil water storage capacity. Darker shades represent greater capacity.*

Figure 21 depicts soil water storage capacity for the hypothetical watershed. Soil characteristics determine how much water can be stored in soil. Soils with large, well-connected pore spaces will hold little water against the pull of gravity. Soils with fine particles or ones with a mix of particle sizes can hold great quantities of water in storage. Plant's roots and other organic material also affect soil water storage. Where roots have formed channels in the soil, water will drain easily, reducing storage. Note that the soil under the mature forest has finer particles than what lies under the development. The soil under the field and wetland is even finer. Thus, the wetland and field have the highest soil water capacity. The mature forest has slightly better storage capacity than the secondary growth forest because of soil type. The developed area has the smallest storage capacity, partly because of soil type and partly because heavy equipment has compacted the soil, further reducing storage capacity.

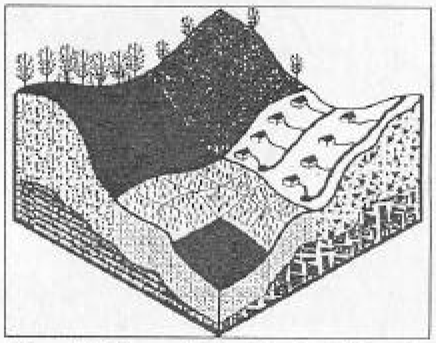

Figure 22. *Transpiration. Darker shades depict greater transpiration.*

In the hypothetical watershed, plant transpiration largely determines evapotranspiration. Dense, well-mixed vegetative cover have high transpiration levels while areas with little cover have low levels. This is seen in Figure 22. The mature forest has the most vegetation and the highest evapotranspiration level. The development has little vegetation and low evapotranspiration. Wetlands tend to produce lush vegetation which transpire a lot of water.

Refer back to the section on runoff and Figure 19 on page 24 for the discussion on infiltration.

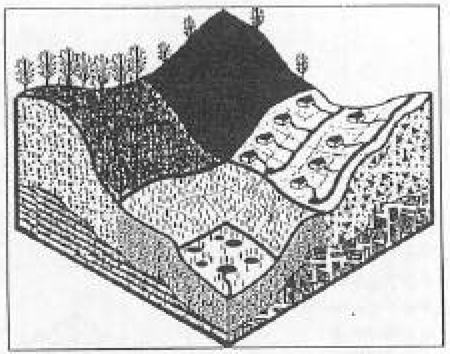

Figure 23. Ground water recharge. Areas with high recharge have darker shading.

Figure 23 shows the major areas of ground water recharge for the hypothetical watershed. Ground water recharge will be highest where i) soil has low capacity for storing water, ii) plants draw up the least water, and iii) infiltration rates are high. The secondary growth forest has the highest ground water recharge capacity because of its high infiltration and moderate evapotranspiration rate and soil water storage capacity. Despite its high evapotranspiration rates, the high infiltration rate and moderate soil water capacity of the mature forest give it fairly high ground water recharge potential. The low infiltration rate (due to impervious surfaces) of the developed area means that it has a low recharge potential even though it has a soil with low storage capacity.

Evapotranspiration

Transpiration, depression storage, and soil water storage combine to influence the remaining element in the water budget—evapotranspiration. Transpiration plays the largest role in determining evapotranspiration. Soil water storage, in turn, affects transpiration by dictating how much water is available to plants and how difficult it is for roots to take it up. Depression storage impacts the evaporation part of evapotranspiration since most evaporation comes from exposed water in puddles, ponds, lakes, and streams. Figure 24 repeats the illustrations shown earlier in the chapter.

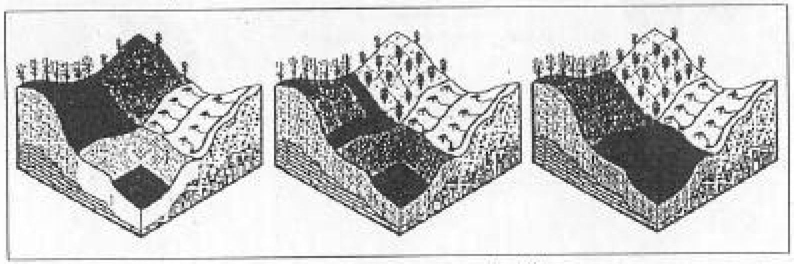

Figure 24. Transpiration, depression storage, and soil water storage

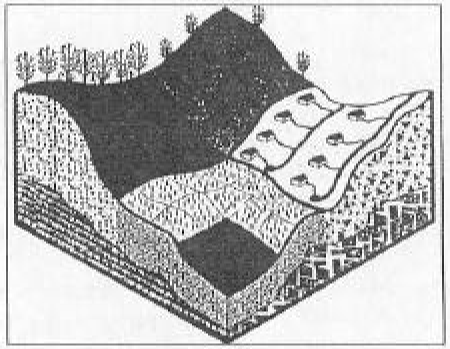

Figure 25. Evapotranspiration. Areas of greatest evapotranspiration have darker shading.

You will notice in Figure 25 that, despite the influence of depression storage and soil water storage, the map of zones with high evapotranspiration matches that of transpiration. This indicates that in the hypothetical watershed the effect of transpiration outweighs any variations in soil water storage or depression storage. This will not always be true. For example, in hot, arid regions evaporation plays an important role. In such a landscape, depression storage will become the dominant influence over evapotranspiration.

Mapping Hydrologic Zones

Bringing together information about evapotranspiration, surface runoff, and ground water recharge, develops a picture of how different parts of the watershed affects water's movement through the landscape.

With a given level of precipitation, combinations of land cover, topography, and geology yield varying ratios of runoff, evapotranspiration, and ground water recharge which defines a landscape's hydrologic zones. Figure 26 depicts these ratios and zones. The zones tell what the water budget looks like for each part of the landscape. *Recharge* zones contribute greatly to ground water recharge. *Runoff* zones have high surface runoff. Low runoff and recharge characterize *retention* zones.

In the mature forest, evapotranspiration accounts for most of the water. The secondary growth forest has high evapotranspiration and significant recharge with comparatively little runoff. Developed land produces a lot of runoff. Fields have little recharge and equal amounts of runoff and evapotranspiration. Wetlands have little or no recharge and equivalent levels of runoff and evapotranspiration.

velopment to store storm water and slow runoff. Drainage systems should also strive to maximize infiltration by lengthening runoff paths and minimizing flow velocities.

Hydrologic Zones with High Ground Water Recharge

Hydrologic zones with high ground water recharge also require careful development design. While high infiltration and good drainage in these zones reduce runoff impacts, they are more susceptible to ground water contamination since water drains to the water table quickly without much of the natural filtration that occurs in soil. Land uses that might contribute contaminents to ground water ought to be scattered thinly in high recharge zones.

Potential sources of pollution—such as septic systems—require additional safeguards against ground water recharge; layers of loamy soil, for example, greatly increase storm water retention capacities. While polluted water should be retained and treated near the surface, other cleaner water should be collected and allowed to percolate to ground water, rather than diverted off-site and away from recharge zones.

It is important to enhance recharge in areas where land use has compacted and degraded soil, and reduced infiltration. Leaving such areas vegetated and undisturbed for a period of three to six years loosens and improves soil structure. Mixing organic matter into the soil also improves infiltration on agricultural and other managed lands.

Hydrologic Zones with Low Surface Runoff & Low Ground Water Recharge (Retention Zones)

High retention zones are the most appropriate areas to accommodate development—the exception being wetlands, which should be left undisturbed. In areas where wetlands are mixed with more suitable land, sensitive development can take advantage of wetlands' storm water retention capacities.

Aside from wetlands, other high retention zones include areas with deep, moderately-textured, well drained soil and slow to moderate runoff flows. These areas are most suitable for development because they maintain a balance between ground water and surface runoff impacts. At the same time, development in these areas should not alter essential retention functions. Development and intensive logging often transform naturally high retention zones into areas that generate excessive runoff.

Proper site design can minimize the runoff that reaches recharge or runoff zones. Buffer areas consisting of undeveloped land surrounding intense land use will isolate development from recharge or runoff zones. The same "best management practices" that minimize runoff in high runoff zones can slow the flow of water and allow the natural retention characteristics of the zone to take affect.

Careful design can also maximize filtering benefits. Recall that soil and plants filter water. Slowing runoff and increasing retention increases the opportunity for filtration, extending water's exposure to the filtering affects of soil particles and microbes. In addition, maintaining multiple layers of vegetation rather than clearing shrubs and ground cover will protect the filtering properties of plants.

This discussion favors high retention zones as most suitable for many types of development because careful planning in these zones can minimize surface runoff and ground water impacts while addressing water quality and quantity concerns. High retention zones promote natural water treatment, rather than the disposal of polluted waters to other parts of the watershed.

Conclusion

Although this handbook has dealt almost exclusively with the how land orm and land cover affect water, water also influences land. In the form f glaciers, rivers, and raindrops, water carves valleys, reduces mounains, and erodes hillsides. The availability of clean water affects the comosition and distribution of plants and animals in the landscape. All pecies of plants and animals are adapted to specific water conditions. If and use dramatically alters the amount of surface or ground water, or ven alters the seasonal cycle of their availability, the abundance and disribution of species changes.

Water also influences how and where humans live. People venture into rid regions only at great expense. The quantity and quality of local water supplies translates directly into town and state budgets for reservoirs, pipelines, and purification facilities. Floods continually force back communities that build homes and businesses near rivers. Most states test soil percolation rates of potential house sites for septic systems (a direct measure of infiltration rates) and availability of a clean water supply (often ground water).

That water is critical both to natural *and* human systems underscores its central role in the environment. Not only can land use decisions that disrupt hydrological processes harm plants and animals, but they cost towns and states money. This handbook has introduced the basic concepts of hydrology—focusing especially on how land and water interact. With the these basic concepts, and an understanding of how they fit together, conservationists, planners, developers, and municipal officials are better equipped to protect water resources and the environment through targeted land conservation, smarter site design, and sounder local regulations.

Where to Find Assistance and Information

Literature References

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Technical Assistance

U.S. Natural Resources Conservation Service; offices in each state.

U.S. Geological Survey; offices in each region.

U.S. Weather Service; regional climate centers maintain weather data.

State water resources agencies.

Local university extensions or cooperative extensions.

U.S. Environmental Protection Agency; offices located in each region